On the evolution and properties of AGB stars

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Chapter 7

Dust shells around infrared carbon stars

Abstract

The spectral energy distributions (SEDs) and LRS spectra of 21 infrared carbon stars are fitted using a dust radiative transfer model. The parameters derived are the temperature of the dust at the inner radius ($T_c$), the mass loss rate and the ratio of silicon carbide (SiC) to amorphous carbon dust (AMC). Mass loss rates between a few $10^{-6}$ and $1.3 \times 10^{-4} M_\odot/yr$ are found. The SiC/AMC ratio and $T_c$ are found to decrease with increasing $S_{25}/S_{12}$ ratio. The former correlation may be due to an increasing C/O ratio. The latter correlation may be due to the fact that dust growth continues until the density is too low. For increasing mass loss rates this leads to increasing inner radii and hence to a decrease of $T_c$.

The standard model with a constant mass loss rate and amorphous carbon dust (with $Q_\lambda \sim \lambda^{-\beta}; \beta = 1$ for $\lambda > 30 \mu m$) predicts too much flux at 60 and 100 $\mu m$ compared to the observations. The discrepancy increases with the $S_{25}/S_{12}$ ratio. This indicates that either $\beta > 1$ and/or that the mass loss rate has been lower in the past. Mass loss histories as proposed by Bedijn (1987) and related to thermal pulses are considered. An increase in the mass loss rate by a factor of 3-30 over the past $10^4$ yrs or $\beta$'s in the range 1.2-1.9 both fit the observed IRAS 60 and 100 $\mu m$ flux-densities. Based on six stars where sub-mm data is available there may be evidence for a phase of high mass loss in a distant past. If the mass loss history is related to thermal pulses then three distinct phases of mass loss can be identified from the SED.

Theoretically one expects that $\beta$ decreases or remains constant as the dust continuum temperature decreases. This fact would point to the mass loss histories rather than a steeper slope of the absorption coefficient to explain the observed 60 and 100 $\mu m$ flux-densities. Both mass loss histories predict sub-mm fluxes in better agreement with observations than a high value for $\beta$. If $\beta = 1$ for the most extreme carbon stars (those with $S_{25} \approx S_{12}$) then a mass loss history related to thermal pulses is preferred to the Bedijn-type mass loss history.

The correlation between the duration of the present-day high mass loss phase and the $S_{25}/S_{12}$ ratio and between the SiC/AMC ratio and the $S_{25}/S_{12}$ ratio can be understood if (on average) an increase in the $S_{25}/S_{12}$ ratio implies an increase in progenitor mass.

1 Introduction

One of the characteristics of AGB stars is their large mass loss rate. In the cool circumstellar envelope dust grains form which absorb optical radiation and re-emit it in the infrared. Previous studies of dust shells around AGB stars either concentrated on oxygen-rich Mira's and OH/IR stars (e.g. Rowan-Robinson & Harris 1983a, Bedijn 1987, Schutte & Tielens 1989, Justtanont & Tielens 1992, Griffin 1993) or on the well-known carbon star IRC 10 216 (e.g. Mitchell & Robinson 1980, Martin & Rogers 1987, Le Bertre 1987, Orofino et al. 1990, Griffin 1990). Rowan-Robinson & Harris (1983b) considered a sample of 44 carbon stars but no IRAS and
LRS data were available at the time. Rowan-Robinson et al. (1986) fitted the spectral energy distributions (SEDs) of five carbon stars but fixed the dust temperature at the inner radius at 1000 K, and assumed a dust absorption law of $\sim \lambda^{-1}$ for all wavelengths without considering the presence of silicon carbide (which has a feature near 11.3 $\mu$m). Le Bertre (1988) fitted three carbon stars. Chan & Kwok (1990) fitted (SEDs) of 145 carbon stars with an LRS classification of 4n (indicating silicon carbide emission), and they therefore missed some carbon stars with weak silicon carbide emission and some extreme carbon stars which have an LRS = 2n classification. They fixed the dust temperature at the inner radius at 1500 K and only included silicon carbide dust in their model.

In this paper an attempt will be made to study some detail questions regarding the mass loss rate, mass loss history, dust formation and strength of the silicon carbide feature. To this end fits are made to the spectral energy distributions (SEDs) and LRS spectra of 21 infrared carbon stars. The dust radiative transfer model used, allows for time-dependent mass loss rates. The dust temperature at the inner radius and the amount of silicon carbide to amorphous carbon dust are treated as free parameters. Recently acquired broad-band data at optical (Groenewegen & de Jong 1993a), near-infrared and sub-mm wavelengths (Groenewegen et al. 1993a), and 2-4 $\mu$m spectra (Groenewegen et al. 1993b) supplemented with data available in the literature are used to constrain the radiative transfer models. Preliminary results for three carbon stars were presented by Groenewegen & de Jong (1991).

In Sect. 2 the radiative transfer model is introduced. In Sect. 3 the fits to the SEDs and LRS spectra are presented and the results are discussed in Sect. 4.

2 The model

The radiative transfer model of Groenewegen (1993) is used. This model was developed to handle non-$r^{-2}$ density distributions in spherical dust shells. It simultaneously solves the radiative transfer equation and the thermal balance equation for the dust.

The SED is determined by the dust optical depth, defined by:

$$\tau_\lambda = \int_{r_{inner}}^{r_{outer}} \pi a^2 Q_\lambda n(r) \, dr = 5.405 \times 10^8 \frac{\dot{M} \Psi Q_\lambda / a}{R_\odot v_\infty \rho_d r_c} \int_{1}^{x_{max}} R(x) \frac{R(x)}{x^2} \, dx$$  \hspace{1cm} (1)

where $x = r/r_c$ and $\dot{M}(r) = \dot{M} R(x)$. The units are: the (present-day) mass loss rate at the inner radius $\dot{M}$ in $M_\odot/yr$, $\Psi$ the dust-to-gas mass ratio, $Q_\lambda/a$ the absorption coefficient of the dust over the grain radius in cm$^{-1}$, $R_\odot$ in solar radii, $v_\infty$ the terminal velocity of the circumstellar envelope in km s$^{-1}$, $\rho_d$ the dust grain density in g cm$^{-3}$, $r_c$ the inner dust radius in stellar radii and $x_{max}$ the outer radius in units of $r_c$. The normalised mass loss rate profile $R(x)$ should obey $R(1) = 1$. The velocity law is assumed to be constant in this paper. A dust-to-gas ratio of $\Psi = 0.005$, grain radius $a = 0.1 \mu$m and grain density $\rho_d = 2.0$ g cm$^{-3}$ are adopted. The outer radius is determined in the model by a dust temperature of 20 K, and scattering is neglected (Le Bertre 1988). The main parameters in the model are the dust temperature at the inner radius ($T_c$), the optical depth at some reference wavelength and the ratio of silicon carbide to amorphous carbon dust. The inner dust radius ($r_c$) and the temperature at the inner radius ($T_c$) are uniquely related through the condition of radiative equilibrium. In Sect. 3 the mass loss rate is assumed to be constant, in Sect. 4 a time-dependent mass loss rate is considered.

The central star is represented by a blackbody modified to allow for the characteristic absorption feature in carbon stars at 3.1 $\mu$m:

$$B_\lambda(T_{eff}) \exp \left( -A e^{-\left(\frac{\lambda-b\lambda}{\lambda}\right)^2} \right)$$  \hspace{1cm} (2)
with $\lambda_0 = 3.1 \, \mu m$. This novelty is introduced to be able to directly fit the observed 2-4 $\mu m$ spectra of some stars. Following Groenewegen et al. (1993b) $A = 4.605$ and $\Delta \lambda = 0.075 \, \mu m$ are adopted. A value of $A = 4.605$ means that in a star without a circumstellar shell the flux in the feature at 3.1 $\mu m$ is 1% of the continuum. The effective temperatures and luminosities of Galactic carbon stars are poorly known. Canonical values of $T_{\text{eff}} = 2500$ K and $L = 7050 \, L_\odot$ are adopted throughout this paper (the mean luminosity of carbon stars in the LMC, Frogel et al. 1981). This implies $R_* = 447 \, R_\odot$. 

**Figure 1:** The LRS spectrum of IRAS 17172–4020 fitted with different species of dust containing $x$% silicon carbide and $(100-x)$% amorphous carbon. From top to bottom: (a) $\alpha$-SiC ($x = 10$), (b) $\beta$-SiC ($x = 15$), (c) SiCN ($x = 15$), (d) SiC1200 ($x = 10$) and (e) SiC600 ($x = 10$). The offset between each spectrum is one flux unit. Spectrum (e) has no offset.
For the dust properties a combination of amorphous carbon (AMC) grains and silicon carbide (SiC) grains is assumed. For simplicity, one condensation temperature is used. In principle, SiC and AMC can have different temperature profiles but to take this into account requires two additional free parameters (a second condensation temperature and a dust-to-gas ratio). Since the abundance of SiC is found to be small, the simplification of the temperature profile is justified. In Eq. (1) the value of $Q_\lambda/a$ is calculated from $Q_\lambda/a = z \ (Q_\lambda/a)^{\text{SiC}} + (1-z) \ (Q_\lambda/a)^{\text{AMC}}$ where $z \ (\in [0,1])$ is determined by the fit to the LRS spectrum. The absorption coefficient for AMC is
3. Fitting the SEDs

In Table 1 some general parameters are listed of the stars that are fitted. All are listed in Groenewegen et al. (1992; hereafter paper I), except IRAS 02345+5422 which is a group V star that has a $12 \mu m$ flux-density of 33 Jy, below the limiting flux-density of 100 Jy considered in paper I. The stars have been selected for the availability of as many flux determinations over as large a wavelength region as possible.

Table 1 lists the IRAS-name and AFGL number, the galactic coordinates, the $C_{21}$ ratio (defined

For $\mathrm{SiC}_{1200}$, $\mathrm{SiC}_{600}$, $\mathrm{SiCN}$ and $\beta$-$\mathrm{SiC}$ the absorption coefficients in the range 2.5 to 40 $\mu m$ are taken from Borghesi et al. (1985) applying matrix correction factors of $h = 0.46$ and $\Delta h = -0.3$ (see their Table 4). For $\lambda > 40 \mu m$ the results of Blanco et al. (1991) are used for these species, scaled to 40 $\mu m$. For $\lambda < 2.5 \mu m$ the values of Pégourié (1988) are used. For $\alpha$-$\mathrm{SiC}$ (Pégourié 1988) the data points beyond $250 \mu m$ are extrapolated using $Q_{\lambda} \sim \lambda^{-2.0}$, based on the last two data points listed by him.

1 For $\mathrm{SiC}_{1200}$, $\mathrm{SiC}_{600}$, $\mathrm{SiCN}$ and $\beta$-$\mathrm{SiC}$ the absorption coefficients for several forms of SiC have been listed in the literature. Species considered here are $\mathrm{SiC}_{1200}$, $\mathrm{SiC}_{600}$, $\mathrm{SiCN}$, $\beta$-$\mathrm{SiC}$ (all from Borghesi et al. 1985) and $\alpha$-$\mathrm{SiC}$ (Pégourié 1988). To determine the best suitable choice some test runs were made fitting the SED and LRS spectrum of the star with the strongest SiC feature in the LRS atlas, namely IRAS 17172-4020 (LRS classification 46). Figure 1 shows that $\alpha$-$\mathrm{SiC}$ (Pégourié 1988) gives the best result. The absorption coefficient of $\alpha$-$\mathrm{SiC}$ is adopted for silicon carbide from now on. Figure 2 shows the absorption coefficient $Q_{\lambda}$ for pure AMC and for a mix (by mass) of 90% AMC and 10% SiC for the wavelength region 0.1 - 1000 $\mu m$. Chan & Kwok (1990) concluded that the empirical opacity function they derived resembles that of $\beta$-$\mathrm{SiC}$ and suggested an evolution from $\alpha$-$\mathrm{SiC}$ to $\beta$-$\mathrm{SiC}$ when a star evolves from an optical to an infrared carbon star. Unfortunately they did not publish any detailed fits to the LRS spectra of the stars in their sample. Our results show that excellent fits to most of the LRS spectra can be obtained with $\alpha$-$\mathrm{SiC}$ (cf. Figs. 3-23). Only is the cases of IRAS 20396+4757 (Fig. 5) and IRAS 03229+4721 (Fig. 6) there maybe evidence for the presence of $\beta$-$\mathrm{SiC}$. Previously, Baron et al. (1987) and Papoular (1988) also favoured $\alpha$-$\mathrm{SiC}$ to explain the SiC feature.

In some stars to be discussed later a 30 $\mu m$ emission feature has been observed (AFGL 489, 3068, 3116), in another (AFGL 2632) such a feature is absent (Forrest et al. 1981, Goebel & Moseley 1985). The 30 $\mu m$ feature is not taken into account. The 30 $\mu m$ feature may contribute up to $\sim$30% of the IRAS 25 $\mu m$ flux-density and up to $\sim$10% of the IRAS 60 $\mu m$ flux-density.

Usually, beam effects are neglected in dust radiative transfer calculations. For $\lambda < 7 \mu m$ and between 150 $\mu m < \lambda < 300 \mu m$ a typical beam of 20" is assumed. Between 7 $\mu m < \lambda < 150 \mu m$ the beam effects of the IRAS detectors are taken into account. The information on the spatial response of the IRAS detectors is taken from Table II.C.3, Table IV.A.1 and Fig. IV.A.3 of the Explanatory Supplement (Joint IRAS Science Working Group 1986). The beams of the 12 and 25 $\mu m$ bands are taken to be circular with FWHM values of 60" in the in-scan direction for both detectors. The beams of the 60 and 100 $\mu m$ bands are taken to be Gaussian with in-scan FWHM (full width half maximum) values of 120" and 220" respectively. For $\lambda > 300 \mu m$ the beam width of the JCMT telescope is assumed. This allows a direct comparison with the observed sub-mm flux-densities in some of the program stars. The influence of beam effects is illustrated in Fig. 12 for AFGL 3116. The influence on the near-infrared and IRAS flux-densities is small. The main change is in the far-IR and mm-region.

In the models the calculated flux-density is convolved with the spectral response (Table II.C.5 of the Explanatory Supplement) to compare the predicted flux-densities directly to the flux-densities listed in the Point Source Catalog.
### Table 1: The program stars

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<th>IRAS-name</th>
<th>APGL</th>
<th>l</th>
<th>b</th>
<th>C21</th>
<th>group</th>
<th>A_V</th>
<th>v_∞</th>
<th>P</th>
<th>photometry</th>
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<td>30.0</td>
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<td>20.4</td>
<td></td>
<td>6, 9, 10</td>
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<td>625 (2)</td>
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as 2.5 log(S_25/S_12); the stars are listed in order of increasing C_{21}, the group designation of paper I, the interstellar extinction in the V-band (see below), the terminal velocity of the envelope (see below), the pulsation period either from optical or infrared lightcurves and finally the references to the photometry used to construct the spectral energy distributions (SEDs). The interstellar extinction at V is estimated from the extinction maps of Neckel & Klare (1980), which list observed values of A_V as a function of galactic coordinates and distance, and the Parenago (1940) model for the interstellar extinction (see paper I for the exact form). For the distance the value in Table 2 is used. Both estimates for A_V usually agree and the average value is quoted in Table 1. The terminal velocities can be accurately determined from millimeter observations. The values in Table 1 are taken from the CO and HCN catalog of Loup et al. (1993) or from Groenewegen et al. (in preparation).
The fitting procedure is as follows. Typically four values for the dust temperature at the inner radius ($T_c$) are chosen. The mass loss rate (assumed constant) is varied to fit the SED. The distance is determined by demanding that the predicted and observed IRAS 25 μm flux-density agree. The SiC feature is fitted by changing the (mass) ratio SiC/AMC. This last step is straightforward since the strength of the SiC feature turns out to scale linearly with the adopted SiC/AMC ratio. In choosing the best value for $T_c$ equal weight is given to the fits of the SED and the LRS spectrum. If necessary, the above mentioned steps are repeated for the final choice of $T_c$. The value of the mass loss rate and $T_c$ can both be estimated to within 10%. The best-fitting models are shown in Figs. 3 to 23 (at the end of the chapter) and the corresponding model parameters are listed in Table 2.

The observed SEDs plotted in Figs. 3-23 have not been corrected for interstellar extinction. Reddening vectors are indicated in Figs. 3-23 for the shortest observed wavelength point based on the $A_V$'s is Table 1 and the interstellar extinction curve of Cardelli et al. (1988). The correction for interstellar extinction is usually small compared to the variation in the SEDs due to variability.

Inspection of Figs. 3-23 shows that the quality of the fits to the SEDs and LRS spectra is high with only a few exceptions (08074–3615 and 08171–2134). In some of these cases the poor fit may be due to the fact that only one set of near-IR photometry is available, which makes it uncertain how to join the IRAS data with the near-IR data. When near-IR photometry at minimum and maximum light is available it is possible to estimate the effective phase which the

### Table 2: The fit parameters

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<th>IRAS-name</th>
<th>$T_c$ (K)</th>
<th>M ($M_\odot$/yr)</th>
<th>$r_{inner}$ (kpc)</th>
<th>SiC/AMC</th>
<th>$d$ (kpc)</th>
<th>$\tau_{11.33}$</th>
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<td>19321+2757</td>
<td>900</td>
<td>1.2 $10^{-5}$</td>
<td>7.9</td>
<td>0.03</td>
<td>0.87</td>
<td>0.30</td>
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<tr>
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<td>1100</td>
<td>1.9 $10^{-5}$</td>
<td>6.1</td>
<td>0.05</td>
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<td>1.38</td>
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<td>800</td>
<td>3.8 $10^{-5}$</td>
<td>11.7</td>
<td>0.05</td>
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<td>8.9</td>
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<td>1.05</td>
<td>1.00</td>
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<td>650</td>
<td>9.1 $10^{-5}$</td>
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<td>0</td>
<td>2.11</td>
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<td>19.9</td>
<td>0</td>
<td>3.99</td>
<td>0.93</td>
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<td>700</td>
<td>1.3 $10^{-4}$</td>
<td>18.3</td>
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<td>2.42</td>
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<td>20.5</td>
<td>0</td>
<td>0.93</td>
<td>1.19</td>
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<tr>
<td>21318+5631</td>
<td>700</td>
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<td>17.7</td>
<td>0</td>
<td>1.47</td>
<td>1.36</td>
<td>43.7</td>
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</tr>
</tbody>
</table>
| 15471–5644 | 700 | 8.5 $10^{-5}$ | 17.4 | 0 | 1.73 | 1.21 | 38.9 | $T_{eff} = 2000$ K
IRAS observations represent.
The fits to the 2-4 μm spectra ranges from poor (e.g. 11318–7256) to excellent (e.g. 13477–6532). In the stars where there is disagreement the predicted strength of the 3.1 μm feature is always too small. This is not due to an underestimate of the strength of the 3.1 μm feature in the central star as this was already adopted to be strong (cf. Eq. 2). The discrepancy may point to an additional contribution of circumstellar 3.1 μm absorption (see the discussion in Groenewegen et al. 1993b). Part of the discrepancy may is some cases also be due to the difference in phase between the different observations. It would be interesting to monitor the 2-4 μm region during a pulsation period in a few stars to investigate how large the changes in the continuum and the 3.1 μm feature are. In the cases that no observed 2-4 μm spectra are available, the line profiles are a prediction of the expected strength.
The derived mass loss rates are subject to the following systematic effects. Following Eq. (1) the mass loss rate scales like ~R, v_∞/κ. For a constant effective temperature, the derived mass loss rates (and distances) scale like √L. The opacity at 60 μm for the adopted absorption coefficient (κ = 3 Q/4 a ρa) is 68 cm²gr⁻¹. This is about a factor of 2 lower than the usually quoted value of ~160 cm²gr⁻¹ (see e.g. Jura 1986). Since the mass loss rate scales like 1/κ, the values quoted in Table 2 may be systematically too high by a factor of 2.
The influence of the adopted effective temperature of the underlying central star on the SED is explicitly verified in the cases of AFGL 2632 and AFGL 3068, where a model with T_\text{eff} = 2000 K is run (see Table 2). The influence of the effective temperature is twofold. Firstly, there is a direct effect in the stellar contribution to the emerging flux. For most infrared stars (like AFGL 3068) this effect is negligible since the stellar flux is completely reprocessed in the dust shell. Secondly, the effective temperature influences the temperature distribution of the dust (through the equation of radiative equilibrium). To obtain an optical depth equal to that for the standard model with T_\text{eff} = 2500 K, the mass loss rates need to be changed by ≤10% and the distances need to be changed by ≤5%. The decrease in the V-magnitude for AFGL 2632 is 1.9, indicating that for optical carbon stars and carbon stars with optical thin envelopes the uncertainty in the adopted effective temperature affects the fit of the SED in the optical part of the spectrum. The main change compared to the standard model is in the inner dust radius which changes according to r_\text{inner} ~ T_\text{eff}^{-2/3} for amorphous carbon dust.
The ratio (by mass) of silicon carbide dust to amorphous determined is listed in Table 2. This ratio depends on the adopted absorption coefficients for SiC and AMC. Groenewegen & de Jong (1991), who used an opacity for AMC about 5 times higher than in the present study, found SiC/AMC = 0.4. Egan & Leung (1991) adopt SiC/AMC = 0.07 in their analysis of optical carbon stars without commenting on their particular choice. Egan & Leung use the same opacity for SiC and a similar one for AMC as in this study. The ratio they find for optical carbon stars agrees well with the ratio found in the least obscured stars in this sample.

4 Discussion and conclusion

In Fig. 24 the derived quantities T_e, the ratio of SiC to AMC and the mass loss rate are plotted as a function of C_{21}. The mass loss rate increases from a few 10⁻⁶ M_☉/yr to ~1 10⁻⁴ M_☉/yr for the most extreme carbon stars. Both the temperature of the dust at the inner radius and the ratio SiC/AMC decrease with increasing C_{21}. The dust temperature at the inner radius is for most stars considerably below the canonical condensation temperature of carbon-rich dust. A similar effect was found by Onaka et al. (1989) from fitting dust shell models to the LRS spectra of about 100 optically-bright oxygen-rich Mira variables. They explained this in terms of variations in the location of dust formation related to stellar pulsation.
The assumption of an unique inner dust shell radius is an oversimplification of the dust formation...
4. Discussion and conclusion

and growth process around long-period variables (LPVs). This has been studied theoretically by Fleischer et al. (1992) who show that the dust-to-gas ratio is a complicated function of radius, due to the periodic generation of shock waves. The derived inner dust radius should therefore be considered as the characteristic radius at which the dust formation has essentially been completed. While the mass loss rates differ by almost a factor of 50 in the sample, the density at the inner dust radius \( \rho_{\text{inner}} \sim \dot{M}/v_{\infty} r_{\text{inner}}^2 \) varies by less than a factor of 4. This suggests that the density beyond a certain radius is too low for further dust formation. This radius effectively corresponds to the inner radius we derive. For larger mass loss rates (larger \( C_{21} \)) this critical density is reached at larger radii and hence at lower dust temperatures. This
may explain the variation of $T_c$ with $C_{21}$ in the top panel of Fig. 24. One might envision the following dust formation scenario. Condensation probably starts near the normal condensation temperature ($\sim 1500$K) fairly close to the star. The carbon (or SiC) dust grains that are formed are small and do not absorb (Tielens 1990) and therefore do not affect the observed SED. At
4. Discussion and conclusion

Figure 26: The long-wavelength part of the SED (top panel), LRS spectrum (middle panel) and the brightness curve at 1 mm (bottom panel) for AFGL 3116. Along the x-axis of the brightness curve the impact parameter $P$ is plotted ($P \approx 0.03$ corresponds to the stellar radius, $P \approx 0.25$ corresponds to the inner dust radius), along the y-axis $P$ times the emerging intensity. The flux is proportional to $\int_0^{P_{\text{max}}} I(P) P \, dP$. Indicated are the constant mass loss rate case (solid line), the thermal-pulse-type mass loss history (dashed line), the Bedijn-type mass loss history (dashed-dotted line) and a model with a steeper slope of the absorption coefficient (dotted line). In the SED the solid and the dashed-dotted line are indistinguishable. The parameters are given in the text and are chosen to fit the IRAS 60 and 100 $\mu$m flux-densities. The LRS spectra have been normalised at 16 $\mu$m. The line in the bottom panel at 9 $10^{16}$ cm represents the beam size of the JCMT telescope at 1 mm.

larger radii the dust grains have become larger and now have typical absorption properties. The dust-to-gas ratio has increased. The process of dust growth continues until the density is too low for further dust formation.
7. Dust shells around infrared carbon stars

Figure 27: The pulsation period (top panel) and terminal velocity (upper panel) versus $C_{21} = 2.5 \log(S_{25}/S_{12})$ color. The right hand scale of the top panel is the pulsation period converted into a luminosity using the P-L-relation described in the text. The (o) represent the stars in Table 1 for which a pulsation period and well determined expansion velocity exist. The (+) represent additional carbon stars from Jones et al. (1990) and Le Bertre (1992) for which pulsation periods based on infrared light curves exist.

The well-known carbon star IRC 10 216 has $C_{21} = -0.785$, $P = 649$ days and $v_\infty = 15.0$ km s$^{-1}$.

The decrease in strength of the silicon carbide feature with increasing optical depth (cf. Fig. 24 middle panel) had already been noticed by Baron et al. (1987), van der Bliek (1988), Chan & Kwok (1990), and in paper I. Here, it is demonstrated that this is an abundance effect and not an optical depth effect. Because silicon is depleted in the gas phase it has been inferred that practically all silicon is in grains (Sahai et al. 1984). Since silicon is not involved in any nuclear reactions, this suggests that the decrease of the SiC/AMC ratio is either a sequence of decreasing metallicity of the progenitor of the carbon star or a sequence of increasing C/O ratio. The latter possibility derives from the fact that, with nearly all oxygen tied up in CO, the number of carbon atoms to form dust (and molecules like HCN and $C_nH_m$) depends on (C/O-1). A sequence of decreasing metallicity is unlikely for two reasons. First, carbon stars are formed from stars $\geq 1.5$ M$_\odot$ (lifetime $\leq 3$ Gyr). In such relatively young stars the metallicity is expected to be close to solar. Second, one might expect the dust-to-gas ratio to scale with the metallicity. If so, one would expect a decrease in the optical depth with decreasing metallicity (cf. Eq. 1). However, the sequence of decreasing SiC/AMC ratio is a sequence of increasing mass loss rate (i.e. optical depth). If the sequence of decreasing SiC/AMC ratio were indeed a sequence of increasing C/O ratio then one could argue that this would also be a sequence of increasing initial mass, since more massive stars are expected to experience more thermal pulses as carbon stars, resulting in
larger C/O ratios.

Danchi et al. (1990) found that in IRC 10 216 (with C$_{21} = -0.785$) dust forms at $\sim 3$ $R_\odot$ at temperatures 1200-1300 K. Figure 24 suggests that for C$_{21} = -0.785$, $T_c$ lies in the range 900-1300 K. If $T_c = 1300$ K then $r_{inner} \approx 3.2$ $R_\odot$ (cf. Table 2) in good agreement with observations. It would be interesting to perform interferometric observations for group V stars where inner radii of more than 10 stellar radii are predicted (if $T_{eff} = 2500$ K).

Inspecting Figs. 3-23 closely, reveals that the best-fitting models predict too much flux at 100 $\mu$m (and to a lesser extent also at 60 $\mu$m). The ratio of the predicted to the observed 100 $\mu$m flux-density is smallest (1.2) in 11318-7256 and largest (3.0) in 08074-3615. There may be a correlation with C$_{21}$ (Fig. 25). There are two possible explanations. The wavelength dependence of the absorption coefficient ($Q_\lambda \sim \lambda^{-\beta}$) is steeper for $\lambda > 30$ $\mu$m than adopted by me for the amorphous carbon dust species, and/or the mass loss rate has been lower in the past.

Two mass loss histories are considered. Bedijn (1987) proposed that the mass loss rate at the tip of the AGB varies like:

$$\dot{M}(t) = \frac{\dot{M}_0}{(1-t/t_0)^\alpha} \quad (t < t_0)$$

Suppose the mass loss rate has increased by a factor of $f$ in the last $\Delta t$ years and the present-day (time $t_1$) mass loss rate is $\dot{M}_1$. These parameters are related to $\dot{M}_0$ and $t_0$ as follows:

$$t_0 = t_1 + \frac{\Delta t}{f^{1/\alpha} - 1}$$

$$\dot{M}_0 = \dot{M}_1 t_0^{-\alpha} \left(\frac{\Delta t}{f^{1/\alpha} - 1}\right)^\alpha$$

Values for $\alpha$ between 0.5 and 1 have been proposed in the literature (Baud & Habing 1983, Bedijn 1987, van der Veen 1989). In the following calculations $\alpha = 0.75$ is used, expecting that the results are qualitatively similar for $\alpha = 0.5$ or 1. The relevant time scales are the flow time scale through the envelope and $\dot{M}/\dot{M}$. For the models in the previous section the time for a dust particle to travel from the inner to the outer radius is $\sim 3.5 \times 10^4$ yrs. The relevant time scale on which the mass loss rate must change to give appreciable changes in the SED is therefore shorter than this and in the present study adopted to be $\Delta t = 10^4$ yrs.

The observation that some AGB stars make loops in the IRAS color-color-diagram (Willems & de Jong 1988, Zijlstra et al. 1992) indicates that the mass loss rate depends on the phase in the thermal-pulse cycle (cf. Groenewegen & de Jong 1993b). The second mass loss history considered here is a sudden drop in the mass loss rate by a factor of $f_1$, $\Delta t_1$ years ago. Based on theoretical arguments a ratio of the mass loss rate in the quiescent H-burning phase to that in the luminosity dip is adopted of $f_1 = 30$.

For 17 stars in the sample, $\beta \left(Q_\lambda \sim \lambda^{-\beta}\right)$ for $\lambda > 30$ $\mu$m), $f$ (for the Bedijn-type mass loss history) and $\Delta t_1$ (for the thermal-pulse-type mass loss history) are determined by fitting the IRAS 60 and 100 $\mu$m flux-densities. For $T_c$ the values in Table 2 are used. For some stars the present-day mass loss rate has been changed to give the same fit in the optical and NIR as for the constant mass loss rate case. The following range in values is found: $\beta = 1.2-1.9$, $f = 3-30$ and $\Delta t_1 = 340-2900$ yrs.

Changing $f_1$ to 20 or $\infty$ introduces a 20% change in $\Delta t_1$. Not surprisingly, the highest values for $\beta$ and $f$ and the lowest values for $\Delta t_1$ are found for the stars where the constant mass loss rate case predicts the highest 100 $\mu$m flux-density compared to the observations (cf. Fig. 25). The different models are illustrated in Fig. 26 for AFGL 3116, for which $\beta = 1.6$, $f = 11$ and $\Delta t_1 = 720$ yrs are derived. Since the absorption coefficient is changed only for $\lambda > 30$ $\mu$m there
is no change in the LRS spectrum. The fit at sub-mm wavelengths is noticeably worse than the two mass loss history models (see the brightness curve in the bottom panel of Fig. 26). This is found for all six stars where sub-mm data is available to make the comparison.

The difference between the two mass loss histories is that the Bedijn-type history also changes the emission close to the star. This is demonstrated in the brightness curve and in the LRS spectrum where the Bedijn-type mass loss history gives the steepest slope. For AFGL 3116, with \( f = 11 \), this effect is not so large but for the most extreme carbon stars (with \( f \geq 20 \)) the Bedijn-type mass loss history predicts LRS spectra which are steeper than observed. Another effect of the Bedijn-type mass loss history is that the present-day mass loss rate is higher than that for the thermal-pulse-type mass loss history and the constant mass loss rate case. For AFGL 3116 this is only a 3% effect, for the most extreme carbon stars this amounts to 20%.

A combination of a steeper slope in the absorption coefficient and a mass loss history is also possible. For \( \beta = 1.3 \), which would fit the 60 and 100 \( \mu \)m data of all moderate infrared carbon stars, I find \( f = 5 \) and \( \Delta t_1 = 1600 \) yrs, for AFGL 3116. In that case the Bedijn-type and the thermal-pulse-type mass loss history can equally well fit the observations.

With both the Bedijn mass loss history and the mass loss history related to thermal pulses the observed IRAS 60 and 100 \( \mu \)m flux-densities can be fitted. For all six stars where sub-mm data is available the observations in the sub-mm wavelength range lie above the model predictions (see Fig. 26 for AFGL 3116). There are several possibilities to explain this discrepancy: (1) there is a contribution of CO line emission to the sub-mm fluxes. For IRC 10 216 this contribution at 1.3 mm has been estimated to be 30% (Walsmsley et al. 1991), (2) this is due to pulsational variability. This is unlikely, since the probability to observe six stars above the mean flux level is only \( (\frac{1}{2})^6 = 1.6\% \), (3) it may point to a detached shell, due to a phase of high mass loss in a distant past. This would be incompatible with the Bedijn mass loss history in which mass loss on the AGB changes in a continuous way. In the case of the mass loss history related to thermal pulses it would point to three distinct phases of mass loss: a present-day phase of high mass loss, a phase of lower mass loss which ended \( \Delta t_1 \) years ago and a phase of high mass loss in a distant past, or (4) the sub-mm fluxes may sample a region where the circumstellar shell is slowed down by the interstellar medium, leading to a (relative) higher density and hence larger flux. The most powerful method to trace the density distribution of the dust is by mapping the circumstellar shell. This is illustrated in Fig. 26 where the Bedijn-type mass loss history and the mass loss history related to thermal pulses predict the same sub-mm fluxes (top panel) but have different brightness curves (bottom panel).

The value of \( \Delta t_1 \) represents the duration of the present-day high mass loss rate, associated with the phase of quiescent H-burning in the thermal pulse mass loss history. The fact that in Fig. 25 no stars are found with red \( \text{C}_2 \) colors and \( S_{100}(\text{predicted})/S_{100}(\text{observed}) \leq 1.5 \) implies that the derived values for \( \Delta t_1 \) are comparable to the maximum duration of the present phase of high mass loss. This implies interpulse periods of \( \leq 10^3 \) yrs and hence relative high core masses (i.e. initial masses). By default this implies on average lower core (and initial) masses for the bluer carbon stars with larger values for \( \Delta t_1 \). This then suggests that the reddest carbon stars have on average more massive progenitors than the blue infrared carbon stars.

The variation of \( \beta \) with \( \text{C}_2 \) (cf. Fig. 25) could be interpreted, at first sight, as an increasing contribution of crystalline carbon (with \( Q_\lambda \sim \lambda^{-2} \)) relative to amorphous carbon (with \( Q_\lambda \sim \lambda^{-1} \)). Baron et al (1987) find evidence that the proportion of crystalline to amorphous carbon increases with increasing temperature of the dust continuum, in agreement with the theoretical expectation (Gail & Sedlmayer 1984). This would point to the mass loss history models rather than the steeper slope in the absorption coefficient as the correct model to explain the IRAS 60 and 100 \( \mu \)m flux-densities. The mass loss history models predict sub-mm fluxes in better agreement with
the observations than the model with the steeper absorption coefficient. One point of discussion during the last few years has been whether the sequence of infrared carbon stars from low-to-high $S_{25}/S_{12}$ ratio is a sequence in mass or in time (Habing 1990). In the discussion above both the decrease of the SiC/AMC ratio and the decrease in $\Delta t_1$ (c.q. the increase in $f$) with $C_{21}$ can be taken as evidence for an increasing progenitor mass. In Fig. 27 the pulsation period and $v_\infty$ are plotted versus $C_{21}$, quantities which may further assess this question. The pulsation period is a direct measure of the luminosity through the P-L relation. The relation used here is $M_{bol} = 0.23 - 1.86 \log P$, based on the P-L-relation of Feast al. (1989) for carbon-rich Miras in the LMC and a distance modulus to the LMC of 18.50 (Panagia et al. 1991). There may be a systematic effect due to the metallicity difference between the Galaxy and the LMC, which is neglected here. There may be a weak correlation of $P$ with $C_{21}$ but the scatter is large. Some stars have a luminosity above the adopted mean of 7050 $L_\odot$.

A terminal velocity in excess of 17.5 km s$^{-1}$ is generally viewed as indicative for a more massive star (e.g. Barnbaum et al. 1991). Figure 27 suggest that stars with $v_\infty \gtrsim 17.5$ km s$^{-1}$ are confined to $C_{21} \lesssim 0.2$, while stars with lower terminal velocities are found over the whole range in color. The apparent anti-correlation between terminal velocity and infrared colors may be explained as follows. Habing et al. (1993) recently showed that for stellar winds driven by radiation pressure on dust grains, the expansion velocity as a function of $\dot{M}$ first increases, reaches a maximum and then decreases. Possibly the expansion velocities of the present sample represent the latter regime. An alternative scenario is the following. The terminal velocities are measured from CO(1-0) and CO(2-1) emission lines which are formed at several $10^{17}$ cm from the star. If the CO is associated with a previous phase of lower mass loss (= lower luminosity in the case of the thermal-pulsing mass loss history) then the CO outflow velocities are probably lower than the present-day outflow velocities. This phenomenon occurs e.g. in S Scy, an optical carbon star with a detached shell, where the present-day expansion velocity is $\sim 5$ km s$^{-1}$ while the shell expands with 16.5 km s$^{-1}$ (Olofsson et al. 1992, Yamamura et al. 1993).

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Figure 3: The fit to the SED, LRS spectrum and 2-4 μm region of IRAS 11318–7256. For the corresponding parameters see Table 2. The model is represented by the solid line, the observations by the symbols and the ragged lines. The sub-mm and the most uncertain optical and near-IR data points have errorbars. Observations at minimum and maximum light are connected. Upperlimits are indicated by a V. The line near 1 μm represents the reddening vector at the shortest observed wavelength point (see Table 1). The predicted LRS spectrum and 2-4 μm spectrum are scaled to the observations. The scaling factor $f$ (in the sense that the plotted model flux equals the calculated model flux multiplied by $f$) is 1.075 for the LRS spectrum and 0.675 for the 2-4 μm spectrum.
Figure 4: As Fig. 3 for IRAS 14484–6152. The scaling factor for the LRS spectrum is 1.104.
Figure 5: As Fig. 3 for IRAS 20396+4757. The scaling factor for the LRS spectrum is 0.888.
Figure 6: As Fig. 3 for IRAS 03229+4721. The scaling factor for the LRS spectrum is 1.097.
Figure 7: As Fig. 3 for IRAS 07217–1246. The scaling factor for the LRS spectrum is 0.906.
Figure 8: As Fig. 3 for IRAS 15194–5115. The scaling factor for the LRS spectrum is 0.86.
Figure 9: As Fig. 3 for IRAS 07098–2012. The scaling factor for the LRS spectrum is 0.821.
Figure 10: As Fig. 3 for IRAS 16545−4214. The scaling factor for the LRS spectrum is 0.665.
Figure 11: As Fig. 3 for IRAS 06342–0328. The scaling factor for the LRS spectrum is 0.837.
Figure 12: As Fig. 3 for IRAS 23320+4316. The scaling factor for the LRS spectrum is 1.00. The dashed line is the same model without beam effects.
Figure 13: As Fig. 3 for IRAS 19321+2757. The scaling factor for the LRS spectrum is 0.85.
Figure 14: As Fig. 3 for IRAS 09116–2439. The scaling factor for the LRS spectrum is 0.928.
Figure 15: As Fig. 3 for IRAS 13477–6532. The scaling factor for the LRS spectrum is 1.097, for the 2-4 μm spectrum 0.758.
Figure 16: As Fig. 3 for IRAS 06012+0328. The scaling factor for the LRS spectrum is 0.800.
Figure 17: As Fig. 3 for IRAS 19594+4047. The scaling factor for the LRS spectrum is 0.882, for the 2-4 μm spectrum 0.612.
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Figure 18: As Fig. 3 for IRAS 08074–3615. The scaling factor for the LRS spectrum is 0.707, for the 2-4 μm spectrum 0.640.
Figure 19: As Fig. 3 for IRAS 02345+5422. The scaling factor for the LRS spectrum is 0.833, for the 2-4 μm spectrum 1.357.
Figure 20: As Fig. 3 for IRAS 08171–2134. The scaling factor for the LRS spectrum is 1.314.
Figure 21: As Fig. 3 for IRAS 23166+1655. The scaling factor for the 2-4 μm spectrum is 1.79.
Figure 22: As Fig. 3 for IRAS 21318+5631. The scaling factor for the LRS spectrum is 0.86.
Figure 23: As Fig. 3 for IRAS 15471–5644. The scaling factor for the LRS spectrum is 0.759.